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14. ABSTRACT

Eddy-resolving simulations of the Atlantic and Pacific Oceans were performed using the HYbrid Coordinate Ocean Model (HYCOM) at 1/120 (-1 km mid- latitude) resolution. HYCOM is isopycnal in the open, straqfied ocean, but makes a dynamically smooth transition to a terrain-following coordinate in shallow water and to pressure coordinates in the mixed layer and/or unstratified regions via the layered continuity equation. This approach retains the advantages that each individual vertical coordinate system offers. After a series of free-running simulations, a data assimilative version of the 1/120 Atlantic HYCOM has been developed into a near real-time nowcast/forecast system. Sea surface height analyses of available satellite altimeter data are assimilated into the model. A nowcast and a 10-day forecast are produced each week. Near real-time results are available via the HYCOM consortium for data assimilative ocean modeling web page at <http://hycom.rsmas.miami.edu>.

15. SUBJECT TERMS

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Basin-scale Ocean Prediction with the HYbrid Coordinate Ocean Model

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Abstract

Eddy-resolving simulations of the Atlantic and Pacific Oceans were performed using the HYbrid Coordinate Ocean Model (HYCOM) at 1/12° (~7 km mid-latitude) resolution. HYCOM is isopycnal in the open, stratified ocean, but makes a dynamically smooth transition to a terrain-following coordinate in shallow water and to pressure coordinates in the mixed layer and/or unstratified regions via the layered continuity equation. This approach retains the advantages that each individual vertical coordinate system offers. After a series of free-running simulations, a data assimilative version of the 1/12° Atlantic HYCOM has been developed into a near real-time nowcast/forecast system. Sea surface height analyses of available satellite altimeter data are assimilated into the model. A nowcast and a 10-day forecast are produced each week. Near real-time results are available via the HYCOM consortium for data assimilative ocean modeling web page at <http://hycom.rsmas.miami.edu>.

1. Introduction

The principal goal of this research effort is a second-generation operational eddy-resolving global ocean prediction system using the HYbrid Coordinate Ocean Model (HYCOM) with assimilation of ocean data. This is the first of two DoD HPC Challenge projects aimed at transitioning this system to the Naval Oceanographic Office (NAVO) in 2006 where it will run on scalable computers at the MSRC. HYCOM is isopycnal in the open, stratified ocean, but makes a dynamically smooth transition to a terrain-following coordinate in shallow coastal regions, and to z-level (pressure) coordinates in the mixed layer and/or unstratified seas. The hybrid coordinate extends the geographic range of applicability

of traditional isopycnic coordinate circulation models toward shallow coastal seas and unstratified parts of the world ocean. The hybrid model maintains the advantages of an isopycnal model in stratified regions while allowing higher vertical resolution near the surface and in shallow coastal areas, hence providing a better representation of the upper ocean physics and biochemical processes.

Our previous research indicates that 7 km in mid-latitudes is the minimum resolution required for this task (Hurlburt *et al.*, 1996; Hurlburt and Metzger, 1998; Hurlburt and Hogan, 2000). The goal is 7 km resolution globally, but this HPC challenge project concentrates on the Atlantic and Pacific Ocean basins because the computer power available for operational ocean nowcasting and prediction is not yet sufficient for the entire globe at this resolution. Starting with smaller geographic regions (semi-enclosed seas outside Challenge, and single ocean basins under this project) and with a coarser resolution global model (~60 km at mid-latitudes) is the most cost effective and practical way to reach the global goal in the shortest time. The longer term goal is global resolution of 3–4 km at mid-latitudes by the end of the decade.

2. Problem and Methodology

Traditional ocean models use a single coordinate type to represent the vertical, but model comparison exercises performed in Europe (DYnamics of North Atlantic MOdels - DYNAMO) (Willebrand *et al.*, 2001) and in the U.S. (Data Assimilation and Model Evaluation Experiment - DAMEE) (Chassignet *et al.*, 2000) have shown that no single vertical coordinate - depth, density, or terrain-following - can by itself be optimal everywhere in the world ocean. These and earlier comparison studies (Chassignet *et al.*, 1996; Roberts *et al.*, 1996, Marsh *et al.*, 1996) have shown that the models considered are able

simulate the large-scale characteristics of the oceanic circulation reasonably well, but that the interior water mass distribution and associated thermohaline circulation are strongly influenced by localized processes that are not represented equally by each model's vertical discretization. Ideally, an ocean general circulation model should (a) retain its water mass characteristics for centuries (a characteristic of isopycnic coordinates), (b) have high vertical resolution in the surface mixed layer (a characteristic of z-level coordinates) for proper representation of thermodynamic and biochemical processes, (c) maintain sufficient vertical resolution in unstratified or weakly-stratified regions of the ocean, and (d) have high vertical resolution in coastal regions (a characteristic of terrain-following coordinates).

HYCOM is isopycnal in the open, stratified ocean, but makes a dynamically smooth transition to a terrain-following coordinate in shallow coastal regions, and to z-level coordinates in the mixed layer and/or unstratified seas. The hybrid coordinate is obtained via a fully general continuity equation that allows an arbitrary partitioning between density coordinates and depth coordinates on a time step by time step basis. Historically, ocean models have had problems with dense water overflows that are crucial for accurate simulation of deep water properties and the overall global circulation budget. The hybrid vertical coordinate approach effectively handles such overflow situations, as demonstrated in Figure 1 that shows the Denmark Strait overflow from 1/12° Atlantic HYCOM.

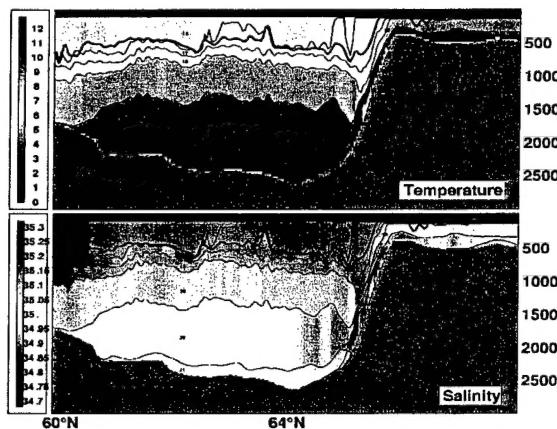


Figure 1. Cross-sections simulated by 1/12° Atlantic HYCOM with 26 layers along 31°W that passes through the Denmark Strait. Top panel shows temperature (red warmer) and the lower panel shows salinity (red more saline), plus layer interface locations (thin lines). Colder, fresher water forms over the shelf in the Nordic Seas and spills over the Denmark Strait, entraining more saline Irminger Sea water as it does so.

We have run several non-assimilative model simulations in both the Atlantic and the Pacific basins, but to date the Atlantic has been the focus of our data assimilation and forecasting efforts. Taken together these two basins cover about 60% of the global ocean. Along with the coarse resolution modeling this is sufficient to give us confidence that the basin-scale results will be adequate to constrain the design of the global 1/12° configuration. The reason for concentrating on the Atlantic only for nowcast and forecast experiments is that it is the basin with the most relevant existing data assimilation experience (from the Miami Isopycnic Coordinate Ocean Model (MICOM)). The free-running simulations (without oceanic data assimilation) will be used to assess the realism, accuracy and dynamical performance of the model in the context of model-data comparisons and comparisons with MICOM. It is essential that the model performs well so that the model will facilitate data assimilation through dynamical interpolation skill rather than fight the data. Simulation skill is also essential for model forecast skill, which allows the use of delayed data.

2.1. Atlantic Configuration.

The computational domain consists of the Atlantic Ocean from 28°S to 70°N, including the Caribbean Sea, the Gulf of Mexico and the Mediterranean Sea, with a horizontal resolution of 1/12° at the equator (~7 km at mid-latitudes) and 26 coordinate surfaces in the vertical. The HYCOM simulation was restarted from a MICOM restart file using monthly climatological European Centre for Medium-range Weather Forecasts (ECMWF) atmospheric fields (including freshwater flux). This allowed us to evaluate the value-added of the hybrid coordinate and of the mixing scheme by comparing the model results to the parallel run using purely isopycnic coordinates (MICOM). Part of the thermohaline circulation is included via relaxation to Levitus temperature, salinity, and interface depth at the northern and southern boundaries. Both buffer zones are 3° wide and the relaxation time scale ranges from 5 days to 120 days inward. ECMWF 10 m wind and thermal forcing (Gibson et al., 1999) are used to drive the surface momentum and heat fluxes. Aside from the relaxation at the lateral boundaries, there is also 50% relaxation to Levitus sea surface salinity. The remaining surface salinity flux comes from evaporation minus precipitation, where the precipitation is from COADS. There is no internal relaxation of any fields outside of the lateral boundaries. Ice is included via a simple energy loan model.

2.2. Pacific Configuration.

The Pacific Ocean domain extends from 20°S to 66°N and 99°E to 78°W and includes the semi-enclosed seas (Bering Sea, Sea of Okhotsk, Japan/East Sea, Yellow Sea, South China Sea) along the northern and western edge of the basin. The horizontal resolution is 1/12° at the equator with 20 vertical coordinate surfaces. A closed boundary exists at 20°S, in the Indonesian Through-flow region and at the Bering Strait. The 10 m isobath defines the land/sea boundary.

A series of simulations of the Pacific Ocean has been completed. One is forced with the Hellerman and Rosenstein (1983) (HR) monthly wind stresses and another with a monthly climatology formed over 1979–93 from ECMWF. The 6-hourly component from the ECMWF operational model over the period Sept. 1994–Sept. 1995 has been added to both monthly wind climatologies to provide high frequency variability. Both use ECMWF thermal forcing. The use of two wind sets allowed an examination of ocean model sensitivity to atmospheric forcing.

2.3. Data Assimilation Techniques.

The data assimilation techniques are an integral part of this project. It currently consists of the assimilation of optimally interpolated fields of sea surface height (SSH). The surface information is transferred to the interior of the ocean using the vertical projection technique of Cooper and Haines (1996). More advanced data assimilation techniques are also being investigated. These include the Singular Evolution Extended Kalman filter (SEEK, Pham *et al.* 1998) and the Reduced Order Information Filter (ROIF, Chin *et al.* 1999).

3. Results

3.1. 1/12° Atlantic HYCO.

A series of Atlantic Ocean simulations has been completed. The first simulation was initialized from a MICOM simulation and forced with monthly ECMWF winds and fluxes. This was continued with the forcing augmented by a high-frequency component from the ECMWF 6-hourly ECMWF operational model. The high frequency component produces more realistic turbulent mixed layer dynamics. This run was extended with 6-hourly Fleet Numerical Meteorology and Oceanography Center (FNMOC) Navy Operational Global Atmospheric Prediction System (NOGAPS) winds and thermal fluxes from July 1999 to July 2002. The model realistically reproduces most basin-scale circulation features,

including the equatorial current systems, North Brazil Current Rings and Loop Current eddy shedding in the Gulf of Mexico. The last requires accurate flow from the Caribbean through the Yucatan Channel. The flow is surface trapped, more intense on the western side of the channel, and exhibits (southward) counter flows at depth. The interannually forced 1/12° Atlantic HYCOM simulation compares well with current meter observations (Figure 2) in this region. However, excessively deep mixed layer depths during winter in the Labrador Sea result in a meridional overturning cell (MOC) that is stronger than observed and tests are underway to improve the accuracy of the mixed layer model. In early 1/12° HYCOM simulations the Gulf Stream separation and North Atlantic Current were realistic, but over time the excessively strong MOC, which increased in strength with the addition of high frequency wind forcing, reduced the realism of these currents in the simulations.

A new 1/12° simulation is underway with several enhancements. These include initialization and boundary relaxation to a more realistic oceanic climatology (the Navy's GDEM3 climatology), a 5 m (10 m minimum depth) coastline (vs. 20 m), monthly river input (vs. annual), Kpar based turbidity derived from SeaWiFS satellite data, stretched (vs. uniformly spaced) sigma levels in shallow water, and variable target densities (for each layer) for more accurate representation of anomalous oceanic regions (such as the Mediterranean).

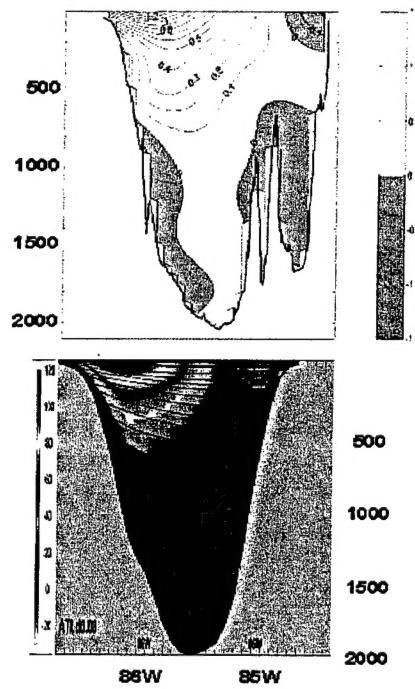


Figure 2. One-year mean meridional flow in the upper 2000 m through the Yucatan Channel from Abascal *et al.* (2001) (top) and 1/12° Atlantic HYCOM (bottom).

3.2. 1/12° Data-Assimilative Near Real-Time Atlantic HYCOM.

A near real-time data-assimilative nowcast/forecast system based on the 1/12° Atlantic version of HYCOM has been running since October 2002. The system assimilates the operational daily Modular Ocean Data Assimilation System (MODAS) SSH analysis of available satellite altimeter data. Currently Geosat Follow-On (GFO), Jason-1 and ERS-2 are used in the analysis. The model is run once per week, includes a 13-day forecast and is forced with the FNMOC NOGAPS products. At the end of the available 5-day NOGAPS forecast, the forcing reverts toward climatology for the remainder of the forecast. Near real-time results are available at the web page of the HYCOM consortium for data assimilative ocean modeling, <http://hycom.rsmas.miami.edu>, under Ocean Prediction. Snapshots and movie loops of the surface fields for both the nowcast and forecast for several different regions of the Atlantic model are available, as are vertical sections of temperature, salinity, and velocity and selected transport sections. A comparison of the model surface fields to an independent frontal analysis of MCSST observations is also included. This analysis is performed operationally at NAVO. Figure 3 shows SSH fields in the Gulf Stream (top) and the Gulf of Mexico (bottom) regions from the near real-time system with the independent frontal analysis overlain. The black segments represent data that are more than 4 days old. The frontal position of the Gulf Stream and the Loop Current show good agreement with the independent observations.

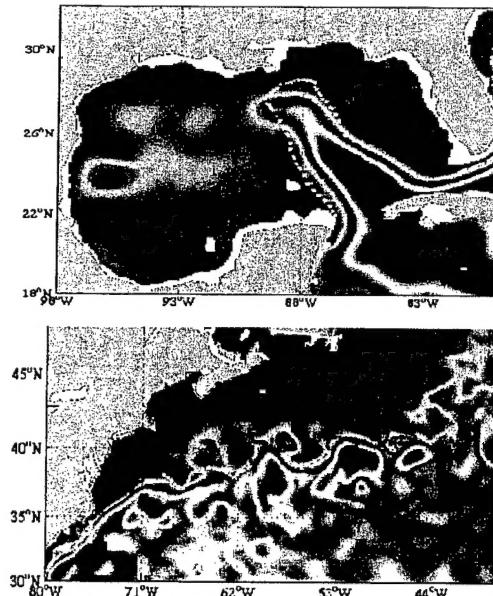


Figure 3. Sea surface height in the Gulf Stream (top) and Gulf of Mexico (bottom) from the data-

assimilative near real-time 1/12° Atlantic HYCOM for 7 May 2003. The white/black line is an independent frontal analysis of MCSST observations performed at the NAVO. The black segments represent data more than four days old.

3.3. 1/12° Pacific HYCOM.

Overall, the large-scale circulation in the 1/12° Pacific HYCOM replicates the observed circulation. Comparisons with dynamic height climatologies (not shown) indicate the basin-wide circulation gyres (tropical, subtropical, sub-polar) and western boundary currents (Kuroshio, Mindanao, Oyashio) are reproduced reasonably well in both the HR and ECMWF wind forced simulations. Initially, the ECMWF forced simulation had an unrealistic sub-gyre within the southern portion of the larger subtropical gyre. This sub-gyre was traced to an anomalously strong wind stress curl dipole signature over the Hawaiian Islands in the ECMWF winds, a feature not found in the HR winds. The sub-gyre was a Sverdrup response to the wind stress curl that extended from the Hawaiian Islands all the way to the western boundary. Subsequent removal of the anomalous wind stress curl dipole led to an ocean model response more consistent with climatological data.

Pacific HYCOM is able to realistically simulate ocean currents with depth as indicated in the following illustrations. Figure 4 shows meridional velocity of the Kuroshio off the east coast of Taiwan in the upper 300 m of the water column. The observational data at 22°N indicates the Kuroshio is a two-core current system that eventually merges into a single core system at 25°N (Liang *et al.*, 2003). The model shows a similar merging of this current system and velocities within 25% of the observed data. In the equatorial Pacific, HYCOM is realistically simulating the tropical surface and subsurface current systems as shown in Figure 5. Observations (Johnson *et al.*, 2001) depict the eastward flowing North Equatorial Countercurrent (~4°–10°N), the Equatorial Undercurrent (EUC) (core at 100 m on the equator), the off equatorial, subsurface Tsuchiya jets (~200–300 m, 4°S and 4°N) and the surface intensified, westward flowing South Equatorial Current. The 1/12° Pacific HYCOM accurately simulates these tropical currents and velocities are within ~15% of the observations. Accurately simulating the depth range of the EUC has been problematic in z-level models because of excessive vertical diffusion. Here the use of hybrid vertical coordinates improves the simulation of the EUC.

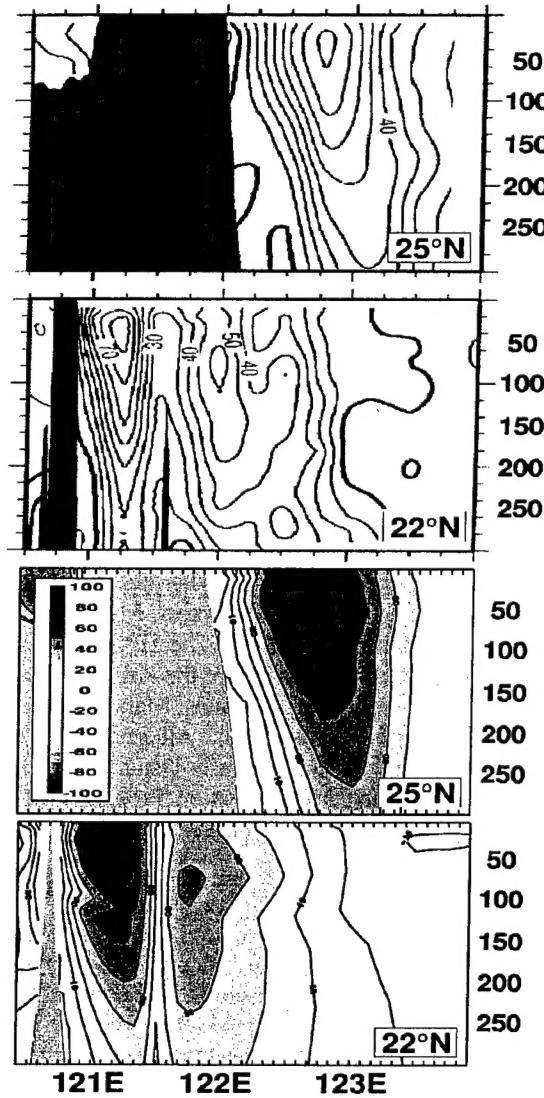


Figure 4. Mean meridional flow in the upper 300 m at 22°N and 25°N off the east coast of Taiwan. Top two panels are a 10-year composite of shipboard ADCP data from Liang *et al.* (2003) and the bottom two panels are a 6-year mean from 1/12° Pacific HYCOM. Yellow/orange/red is northward flow and light blue/blue is southward flow.

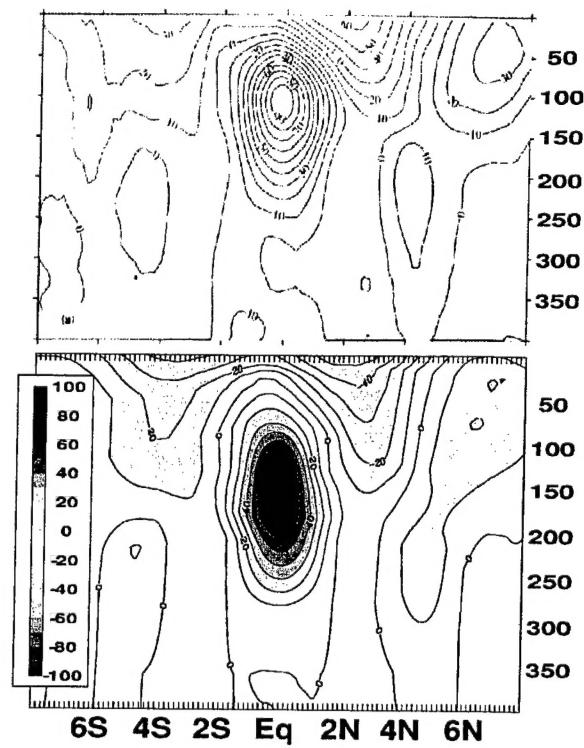


Figure 5. Mean distribution of zonal flow in the upper 400 m of the water column across the equator (8°S-8°N) at 135°W from Johnson *et al.* (2001) (top) and 1/12° Pacific HYCOM (bottom). Yellow/orange/red is eastward flow and light blue/blue is westward flow.

4. Significance to DoD

HYCOM is scheduled to be the ocean model component of the next generation, operational global ocean nowcast/forecast system at NAVO. In 2006 it will replace the existing 1/16° (~7 km mid-latitude resolution) near-global Navy Layered Ocean Model (NLOM). DoD Challenge projects have been essential to the development of the NLOM-based systems, and the computer power required to develop a scientifically based well tested operational global ocean system is such that DoD Challenge will always be essential if the Navy is to make timely deployment of enhanced capabilities. The 1/12° HYCOM system has slightly higher horizontal resolution than the present NLOM, but the primary gain from HYCOM is the extension to the Arctic Ocean (when run globally) and to coastal regions as well as the much higher vertical resolution provided by the hybrid vertical coordinate. In particular, the next generation HYCOM-based system will include a high vertical resolution surface mixed layer and allow interactions between shelf regions and the deep oceans. Thus, this project will

support the need for a fully global eddy-resolving ocean nowcast/forecast system. It will be part of a coordinated operational suite of atmospheric and oceanographic models that run daily in an automated mode. The model will serve as the backbone of a global ocean nowcast/forecast capability that includes providing boundary conditions for even higher resolution, relocatable littoral models. Together these will address the need for littoral or deep water support anywhere in the world. The ocean model and nowcast/forecast systems developed in this project will be designed to take advantage of operational supercomputers and databases.

Applications for the models and the nowcast/forecast systems include assimilation and synthesis of global satellite surface data; ocean prediction; optimum track ship routing; search and rescue; anti-submarine warfare and surveillance; tactical planning; high resolution boundary conditions that are essential for even higher resolution littoral models; sea surface temperature for long range weather prediction; inputs to shipboard environmental products; environmental simulation and synthetic environments; observing system simulations; ocean research; pollution and tracer tracking, and inputs to water quality assessment. Assimilation of satellite altimeter data into the models will make more effective use of near real-time altimeter data from ERS-2, GFO, JASON-1 and follow on satellites (Envisat, JASON-2, NPOESS) via NAVO's Altimeter Data Fusion Center. Sea surface temperature, hydrographic profiles, and other data will be assimilated as well.

The ability to use high-resolution ocean models for data assimilation and forecasting is critical to the development of nowcast/forecast systems. In data assimilation the ocean model provides value added over a purely statistical analysis by (a) including effects of atmospheric forcing on ocean dynamics, (b) providing a source of mean SSH for geoid calculations, (c) providing model statistics and a spun-up first guess for data assimilation, and (d) using model predictive skill to fill in space-time gaps in the data and allowing the use of delayed data by projecting it forward in time. The latter is important when using satellite altimetry because even with rapid dissemination, the average age of data is $\frac{1}{2}$ the time of the satellite repeat cycle (5 days for JASON-1 and 18 days for ERS-2). Accurate model predictive skill is crucial during data outages and is consequently used to improve the nowcast. Finally, high-resolution models are necessary in order to provide skillful forecasts of the evolution of ocean fronts and eddies and other oceanic features.

5. Systems Used

Naval Oceanographic Office: IBM SP-Power4 and SUN F12000. Army Research Laboratory: IBM SP-Power3.

6. CTA.

Climate/Weather/Ocean

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